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A PRELIMINARY MODEL OF THE DISTRIBUTION OF LASER-INDUCED RETINAL LESIONS RESULTING FROM EYE AND HEAD RESPONSES

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A computer program was developed to simulate a pilot's reaction to an ocular exposure from a multiple-pulse laser. The simulation outlines five different scenarios of eye and head responses that are likely to occur in response to a laser exposure. These responses are: (1) closing the eyes; (2) centering the laser image on the fovea with a saccadic eye movement; (3) executing a saccade to avoid foveating the laser beam; (4) holding the eyes stationary relative to the laser beam; and (5) tracking a moving object during the laser exposure.

The simulation modeled the effects of a 1-s laser exposure with pulse rates of 5, 15, or 30 pulses/s and beam angles of 0, 10, 20, or 30 deg eccentric from the point of fixation. The output of the simulation predicted the number and distribution of lesions in terms of retinal topography and acuity under the aforementioned conditions. The results of the simulation demonstrated that the pilot's reactions significantly influenced the number and pattern of lesions deposited on the retina. The most serious threat to vision resulted from an eye

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movement that foveated the laser. Eye movements that diverted the laser from the fovea appeared to minimize the impact on vision. However, further work will be needed to quantify the size and location of the visual field loss. (AU)

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INTRODUCTION

The introduction of multiple-pulse lasers in the modern battlefield represents a potential threat to mission completion. Even a brief exposure to a laser during a crucial part of an aerial maneuver can seriously threaten the vision and safety of an aircrew member. The high repetition rate of these lasers increases the probability that the eye will be exposed to multiple pulses. The potential for ocular injury depends not only on the laser's physical properties but also on the aircrew member's reactions. Therefore, eye and head movements performed at the time of an exposure will play an important role in the disposition of lesions on the retina and the consequent visual impairment.

The purpose of this report is to simulate eye movements associated with visual tasks typically performed by a pilot and to estimate the visual damage resulting from exposure to a high-power, multiple-pulse laser by means of a computer program. The program's output estimates the spatial distribution of the retinal lesions in terms of retinal topography and visual acuity. The results of this simulation will help clarify the effectiveness of a pilot's reactions to minimize laser injury.

At the present stage of development, the simulation does not predict the residual visual acuity following a laser exposure. Such an estimate would require information about the size of the lesion. For now, however, the location of the lesions in terms of the visual acuity supported by the lesioned site will be described. When this model is integrated with a model of laser-induced retinal damage (1), a more complete picture of visual loss will be drawn.

ASSUMPTIONS

The eye movement model contains several assumptions about the optics of the laser and the aircrew member's reaction to it. For purposes of the simulation the laser source is assumed to be located at optical infinity and focused to a point on the retina by the optics of the eye. The laser's energy distribution on the retina and lesion thresholds are assumed to be the same for all angles of beam incidence. A further assumption is that the location of the beam prior to exposure is not known. Therefore, the reaction time of the orienting response reflects the additional time required to locate the laser source (2).

The model of eye movement dynamics used in this simulation is a simplified version of more sophisticated models (3). For purposes of this model horizontal and vertical eye movements were assumed to have equal latencies and velocities. However, the error associated with this

assumption would have only a minimal impact on the estimates of the distribution of retinal lesions.

MODEL

Algorithms were developed to simulate different oculomotor activities representative of various visual tasks. Two categories of scenarios are considered. The first category considers situations in which the pilot sees and responds to the laser. Accordingly, the first category considers only visible laser radiation. In the second category, the pilot continues to perform an ongoing visual task during the laser exposure and does not respond to the laser whether it is visible or not. Thus, the second category scenarios also accommodate effects of the nonvisible portion of the spectrum.

The scenarios postulated for the first category are: (1) the pilot closes his eyes in response to the laser; (2) the pilot foveates the laser source with an acquisition saccade; and (3) the pilot avoids looking at the laser by executing an avoidance saccade. The scenarios included in the second category are: (1) the pilot fixates on some object during the laser exposure; and (2) the pilot tracks a moving object.

LASER PARAMETERS

The model will eventually accommodate the laser properties described. Exposures will be simulated for a neodymium:yttrium-aluminum-garnet (Nd:YAG) laser with wavelength emissions in the visible (532 nm) and infrared (1064 nm) regions. The laser generates a 10-ms or a Q-switched, 20-ns pulse at repetition rates of 5, 15, or 30 pulses/s. The laser image spatial profile on the retina is assumed to follow an exponential decay (4). The pulse train is 1 s in duration. Scenarios are simulated with the laser beam at incident angles of 0, 10, 20, and 30 deg. However, the salient laser parameters at the present stage of model development are the repetition rate, duration, and angle of the incident beam.

EYE AND HEAD MOVEMENTS

Prior to laser irradiation, I assumed that eyes and head are in the normal position; that is, eyes and head are positioned straight ahead and level. This orientation is called the primary line of sight. The model calls for angles of 0, 10, 20, and 30 deg between the laser beam and the primary line of sight. However, the exact location of the laser image on the retina is not specified; rather it can be at any position on a circumference with a radius of any of the preselected angles.

Head movements are introduced into the model under the following conditions. Head movements are performed to assist the execution of large gaze displacements. Most naturally occurring saccades are 15 deg or less. Beyond this amount eye movements are accompanied by head movements (5).

Although a head movement normally accompanies every avoidance saccade, an acquisition saccade must be larger than 15 deg before a head movement is initiated. Head movements typically lag behind eye movements by an average of about 40 ms (6,7). Head movement velocity is a linear function of gaze displacement (6). No head movements are anticipated in the lid closure and fixation scenarios.

SCENARIOS

Lid Closure

In this scenario the pilot immediately responds to the laser by closing his eyes. An exposure of lesion-producing intensity would be expected to elicit a maximum rate of response. The exposure duration is determined by the blink reaction time which is a linear function of the beam eccentricity (8). The function is given by:

$$LCRT = .00127*ECC + .1287 \tag{1}$$

where LCRT is the lid closure reaction time in seconds and ECC is the angle of the laser in degrees. The LCRT is defined as the time it takes for the lid to completely cover the pupil. Reaction times varied from 129 to 167 ms.

Acquisition Saccade

In this scenario the pilot is fixating an object when the laser strikes his eye. Immediately after laser onset he makes a saccade to foveate the laser source. The latency of a saccade is a linear function of the stimulus eccentricity (6) and reflects the reaction time required to find the target (2). When the laser beam is aligned with the visual axis (i.e., when beam eccentricity is zero), then no saccade is made. Eye movement reaction time (EMRT) is given as:

$$EMRT = .0024*ECC + .243 \tag{2}$$

where EMRT is in seconds and ECC is eccentricity in degrees. Reaction times ranged from 243 to 315 ms. Mean velocity of the saccadic eye movement is a linear function of saccade amplitude (9) and is expressed as:

$$MSV = ECC/(.0027*ECC + .037) \tag{3}$$

where MSV is mean saccadic velocity in degrees/second and ECC is the angular distance the eye travels to fixate the laser source. A velocity of 254 deg/s is estimated for the largest displacement. When laser eccentricity exceeds 15 deg, the head also moves to assist acquisition of the beam. Head movement adds a constant velocity of 14.5 deg/s to saccadic velocity for a gaze angle of 30 deg (6).

Avoidance Saccade

In this situation, the pilot tries to avoid the laser source without losing visual contact with his surroundings; he does so with a combined head and eye movement. Such a movement displaces the laser image toward the peripheral retina. Otherwise, the direction of the saccade is not specified. The reaction time of the saccade and head movement is the same as described in the Acquisition Saccade section. Saccadic velocity is estimated to be 321 deg/s based on large amplitude saccades (9). Head velocity is estimated to be 64.5 deg/s (6).

Fixation

In this scenario the pilot's eyes are held steady which causes the laser image to be fixed on the retina. The laser image is located 0, 10, 20, or 30 deg from foveal center. Despite steady fixation, the laser image moves slightly on the retina because the eye is never completely still (10). The amount of movement is described as an area on the retina where the image is located 95% of the time. This area is normally elliptical in shape, but if one assumes that the variances of horizontal and vertical eye movements are equal and independent, then the area can be approximated by a circle. Although these assumptions are not strictly accurate (10,11), the small deviations introduced by these assumptions do not significantly influence the results.

Estimates of the dispersion of the laser image on the retina are computed under two conditions. The first condition predicts the theoretically minimal area of dispersion under ideal conditions of fixation (12). The second condition supposes that the head moves due to movement of the aircraft. Because these conditions are extracted from laboratory research, they provide only rough estimates of dispersions encountered during flight.

Tracking

In this situation the pilot tracks an object moving at a constant angular velocity during the laser exposure. The tracking direction brings the laser beam toward the fovea. At the onset of the laser exposure the laser is positioned 0, 10, 20, or 30 deg from the foveal center and the eye is already following the object. Tracking velocities of 1, 5, 15, and 30 deg/s were selected to represent the normal range of smooth pursuit eye movements (13).

RESULTS

The simulation output describes the distribution of retinal lesions acquired in each scenario. For purposes of describing the area affected, the retina was subdivided into 4 concentric zones, as shown in Figure 1. The inner and outer radii of a zone were measured in degrees from the center of the fovea. Figure 1 also depicts the visual acuity corresponding to each zone. The 20/20 area of central vision extended 24 min-arc from foveal

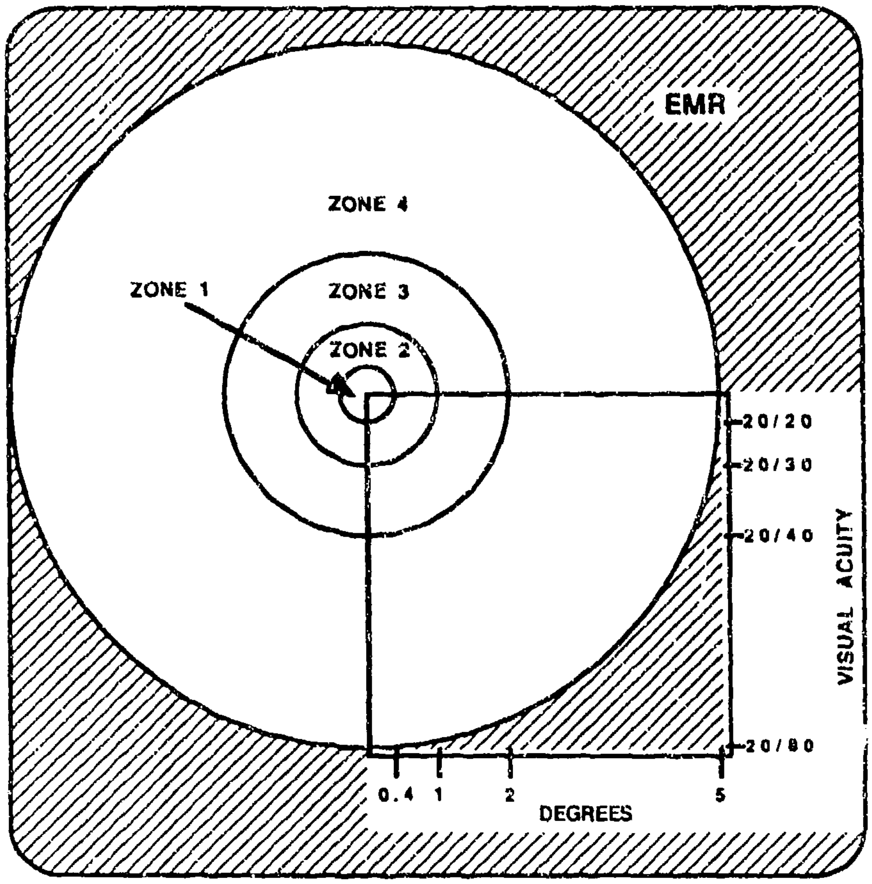

Figure 1. Relation between minimum acuity and angular separation from foveal center with reference to four concentric zones and the extramacular region (EMR).

center (14). This area was represented by Zone 1. The other zones were defined by the minimum acuity level they supported. The extramacular region (EMR) was the area beyond 5 deg radius. In this region visual acuity fell off gradually, and did not support acuity levels above 20/80 (14). The results are displayed in Tables 1-5. The distribution of lesions was estimated for each combination of laser repetition rate and eccentricity.

Lid Closure

Table 1 shows the output of the lid closure scenario. The table shows the number of exposures which fell into Zone 1, the central foveal region supporting visual acuity of 20/20 and better, and the EMR--the area beyond 5 deg supporting less than 20/80 visual acuity. The number of laser exposures absorbed by the retina depended on the reaction time of the blink response. Because the blink response was fast relative to the repetition rate of the laser, most of the exposures were intercepted by the lid. Depending on repetition rate, the lid closure blocked between 4 and 24 of the laser exposures, yielding an 80-87% avoidance rate. Although blink reaction time increased with beam eccentricity, even at large eccentricities, only a small number of additional exposures penetrated the retina.

TABLE 1. DISTRIBUTION OF LESIONS FALLING ON THE FOVEA (ZONE 1) AND THE EXTRAMACULAR REGION PRIOR TO A LID CLOSURE

Eccentricity (deg)	Pulse rate (p/s)	Zone 1 (20/20 VA)	EMR (>20/80 VA)
0	5	1	0
0	15	2	0
0	30	4	0
10	5	0	1
10	15	0	3
10	30	0	5
20	5	0	1
20	15	0	3
20	30	0	5
30	5	0	1
30	15	0	3
30	30	0	6

Blink-related eye movements tended to cause the retinal image position to change during a blink. These eye movements tended to be small--on the order of .5-1.5 deg in vertical amplitude and 0-.5 deg in horizontal amplitude (15). Nevertheless, when the laser was viewed on-axis, a blink-related eye movement might have displaced retinal burns beyond the border of Zone 1, affecting regions of lower visual acuity.

Acquisition Saccade

For scenarios in which an eye movement was made, namely, acquisition saccades, avoidance saccades, and tracking, the output also described the separation distance in degrees (SEP) between lesions. The initial number of lesions prior to an eye movement onset were recorded as IL. The number of lesions located in the various retinal zones were listed and the number of lesions that fall outside these zones were recorded as extramacular lesions.

The output of the acquisition scenario is shown in Table 2 and is displayed graphically in Figure 2. The number and distribution of retinal burns acquired during an acquisition saccade depended on the reaction time and speed of the saccade. These two eye movement parameters caused a majority of the laser exposures to fall on the central fovea (Zone 1) under most conditions of beam eccentricity and repetition rate. For off-axis beam eccentricities the percentage of exposures absorbed prior to the initiation of an acquisition saccade ranged from 30% to 40%. As beam eccentricity increased, fewer exposures fell on the central fovea and more fell in the outer zones. However, there did not appear to be enough exposures landing in these zones to appreciably affect the acuity levels supported by these zones. In contrast, the saccade was effective in exposing the central fovea to the laser pulses, potentially compromising 20/20 acuity levels. The percentage of laser pulses falling in Zone 1 ranged from 40% to 67%.

Avoidance Saccade

As with an acquisition saccade, the effectiveness of an avoidance saccade was dependent on reaction time and speed of the eye movement. These results are displayed in Table 3 and Figure 3. When the laser beam was viewed on-axis, the saccade was effective in directing the laser pulses away from the central fovea. Depending on repetition rate, 60-77% of the laser pulses were displaced from Zone 1. For off-axis beam eccentricities, all of the laser pulses fell in the extramacular region, affecting visual acuity levels of less than 20/80.

Fixation

Table 4 describes the distribution of lesions during fixation for two situations. The first situation assumed that the pilot held his head as steadily as possible. The second situation assumed that aircraft and/or body movement resulted in additional movement of the pilot's head relative

TABLE 2. DISTRIBUTION OF LESIONS OBTAINED DURING AN ACQUISITION SACCADE

				Zone				
				1	2	3	4	EMR
				Visual acuity				
ECC	RR	IL	SEP	20/20	20/30	20/40	20/80	>20/80
0	5	5	0.00	5	0	0	0	0
0	15	15	0.00	15	0	0	0	0
0	30	30	0.00	30	0	0	0	0
10	5	2	31.25	3	0	0	0	2
10	15	5	10.42	10	0	0	0	5
10	30	9	5.21	20	0	0	1	9
20	5	2	43.96	3	0	0	0	2
20	15	5	15.62	9	0	1	0	5
20	30	9	7.81	18	0	2	1	9
30	5	2	53.75	2	0	1	0	2
30	15	5	17.92	8	0	2	0	5
30	30	10	8.96	17	0	3	0	10

ECC = Beam eccentricity (deg)
RR = Pulses/second
IL = Initial lesions
SEP = Separation between lesions (deg)

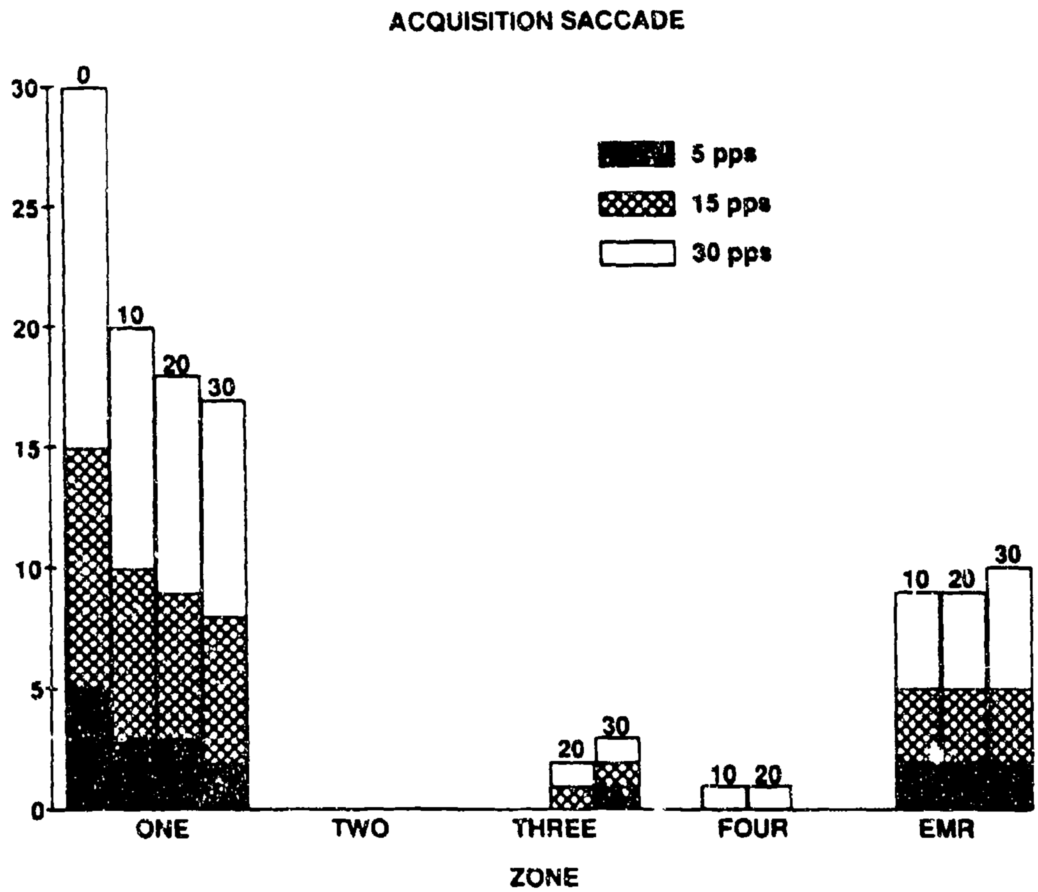

Figure 2. The number of lesions falling within various retinal zones for an acquisition saccade. Data are presented for laser repetition rates of 5 (filled bars), 15 (hatched bars), and 30 (open bars) pulses per second. Numerals above the bars indicate the initial eccentricity of the laser image in degrees. EMR denotes the extramacular region.

TABLE 3. DISTRIBUTION OF LESIONS OBTAINED DURING AN AVOIDANCE SACCADE

				Zone				
				1	2	3	4	EMR
				Visual acuity				
ECC	RR	IL	SEP	20/20	20/30	20/40	20/80	>20/80
0	5	2	77.10	2	0	0	0	3
0	15	4	25.70	4	0	0	0	11
0	30	8	12.85	8	0	0	0	22
10	5	2	77.10	0	0	0	0	5
10	15	5	25.70	0	0	0	0	15
10	30	9	12.85	0	0	0	0	30
20	5	2	77.10	0	0	0	0	5
20	15	5	25.70	0	0	0	0	15
20	30	9	12.85	0	0	0	0	30
30	5	2	77.10	0	0	0	0	5
30	15	5	25.70	0	0	0	0	15
30	30	10	12.85	0	0	0	0	30

ECC = Beam eccentricity (deg)
RR = Pulses/second
IL = Initial lesions
SEP = Separation between lesions (deg)

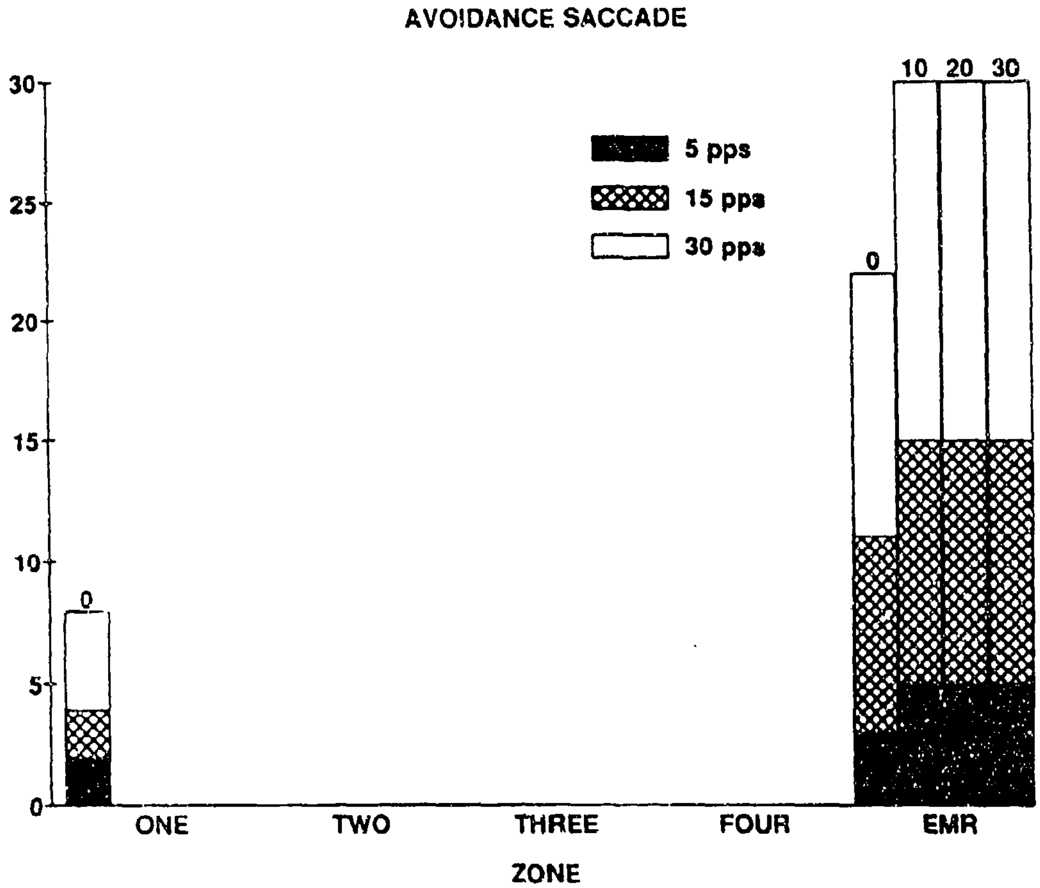

Figure 3. The number of lesions falling within various retinal zones for an avoidance saccade. Repetition rates and initial eccentricity of the laser are the same as in Figure 2.

TABLE 4. THE RELATIONSHIP BETWEEN SNELLEN ACUITY AND THE RETINAL AREA (RADIUS IN min-arc) AFFECTED BY LASER EXPOSURES AT THREE ECCENTRICITIES UNDER TWO CONDITIONS OF HEAD MOVEMENT

Eccentricity (deg)	Head still		Head moving	
	Radius	Acuity	Radius	Acuity
0	3.8	20/20	33.8	20/30
10	3.8	20/120	33.8	20/120
>10	3.8	>20/120	33.8	>20/120

to the laser source. In both situations the laser image moved on the retina, resulting in a scatter of burns around a mean position. However, in the second situation, head movements not compensated by the vestibulo-ocular reflex (VOR) resulted in greater slippage of the image on the retina (12). The dispersion of the laser image on the retina under these two conditions was estimated from data from Skavenski (12) and Steinman (16) and coworkers and scaled for 1 s viewing durations (11).

In Table 4, an area of radius (r) was computed within which 95% of all lesions fell. When the head was as still as possible, the radius was about 3.8 min-arc. When the laser was viewed on-axis, virtually all lesions lay in an area of 20/20 visual acuity (Zone 1). When the laser was viewed eccentrically, the size of the scatter remained the same but the visual acuity affected was different. At 10-deg eccentricity, 20/120 acuity was affected and for eccentricities beyond 10 deg, acuities less than 20/120 were affected. However, the introduction of head movement (experimentally defined as 30 deg-arc horizontal oscillations at .66 Hz) resulted in greater scatter of the image on the retina. For on-axis viewing the lesions were distributed over an area with a radius of 33.8 min-arc--affecting visual acuity of 20/30 and better. For off-axis viewing the affected visual acuity ranged from 20/120 and less for beam eccentricities of 10 deg or more.

Tracking

The output of the tracking scenario is shown in Table 5 and Figures 4-7. The distribution of retinal lesions was described by a linear track with the separation between lesions determined by the tracking velocity (TV) of the eye and the repetition rate of the laser. Separation between lesions varied between .03 and 6 deg. Most of the burns fell in the extramacular area, even though the direction of the tracking eye movement moved the laser image toward the fovea. The greatest threat to the central fovea (Zone 1) occurred when the laser was on-axis from the beginning of the exposure. Slow tracking velocities caused 3% to 43% of the burns to fall in Zone 1; faster tracking velocities displaced the burns to the other zones. When the laser was eccentric to the primary line of sight, only an occasional exposure fell inside Zone 1.

TABLE 5. DISTRIBUTION OF LESIONS OBTAINED DURING VISUAL TRACKING

				Zone				
				1	2	3	4	EMR
				Visual acuity				
ECC	RR	TV	SEP	20/20	20/30	20/40	20/80	>20/80
0	5	1	0.20	3	2	0	0	0
0	5	5	1.00	1	1	1	2	0
0	5	15	3.00	1	0	0	1	3
0	5	30	6.00	1	0	0	0	4
0	15	1	0.07	7	8	0	0	0
0	15	5	0.33	2	2	3	8	0
0	15	15	1.00	1	1	1	3	9
0	15	30	2.00	1	0	1	1	12
0	30	1	0.03	13	17	0	0	0
0	30	5	0.17	3	4	6	17	0
0	30	15	0.50	1	2	2	6	19
0	30	30	1.00	1	1	1	3	24
10	5	1	0.20	0	0	0	0	5
10	5	5	1.00	0	0	0	0	5
10	5	15	3.00	0	1	1	1	2
10	5	30	6.00	0	0	1	1	3
10	15	1	0.07	0	0	0	0	15
10	15	5	0.33	0	0	0	0	15
10	15	15	1.00	1	2	2	5	5
10	15	30	2.00	1	0	2	2	10
10	30	1	0.03	0	0	0	0	30
10	30	5	0.17	0	0	0	0	30
10	30	15	0.50	1	4	4	11	10
10	30	30	1.00	1	2	2	6	19

ECC = Beam eccentricity (deg)
RR = Pulses/second
TV = Tracking velocity (deg/s)
SEP = Separation between lesions (deg)

TABLE 5 (Cont'd.)

				Zone				
				1	2	3	4	EMR
				Visual acuity				
ECC	RR	TV	SEP	20/20	20/30	20/40	20/80	>20/80
20	5	1	0.20	0	0	0	0	5
20	5	5	1.00	0	0	0	0	5
20	5	15	3.00	0	0	0	0	5
20	5	30	6.00	0	0	1	1	3
20	15	1	0.07	0	0	0	0	15
20	15	5	0.33	0	0	0	0	15
20	15	15	1.00	0	0	0	0	15
20	15	30	2.00	1	0	2	2	10
20	30	1	0.03	0	0	0	0	30
20	30	5	0.17	0	0	0	0	30
20	30	15	0.50	0	0	0	0	30
20	30	30	1.00	1	2	2	6	19
30	5	1	0.20	0	0	0	0	5
30	5	5	1.00	0	0	0	0	5
30	5	15	3.00	0	0	0	0	5
30	5	30	6.00	0	0	0	0	5
30	15	1	0.07	0	0	0	0	15
30	15	5	0.33	0	0	0	0	15
30	15	15	1.00	0	0	0	0	15
30	15	30	2.00	0	0	1	1	13
30	30	1	0.03	0	0	0	0	30
30	30	5	0.17	0	0	0	0	30
30	30	15	0.50	0	0	0	0	30
30	30	30	1.00	0	1	1	3	25

(For key to abbreviations, see footnotes on the preceding page.)

DISCUSSION

These results show that a pilot's reaction to a short duration, multiple-pulse laser exposure significantly influences the degree of retinal damage. The most effective strategy for minimizing retinal damage is a lid closure. For the exposure duration and repetition rates examined here, such a strategy reduces the number of retinal burns by 80% or more.

Looking away from the laser by means of an avoidance saccade was another effective way of minimizing injury. An avoidance saccade displaced a significant portion of the laser pulses to the periphery of the retina. Although an avoidance saccade did not afford as much protection as a lid

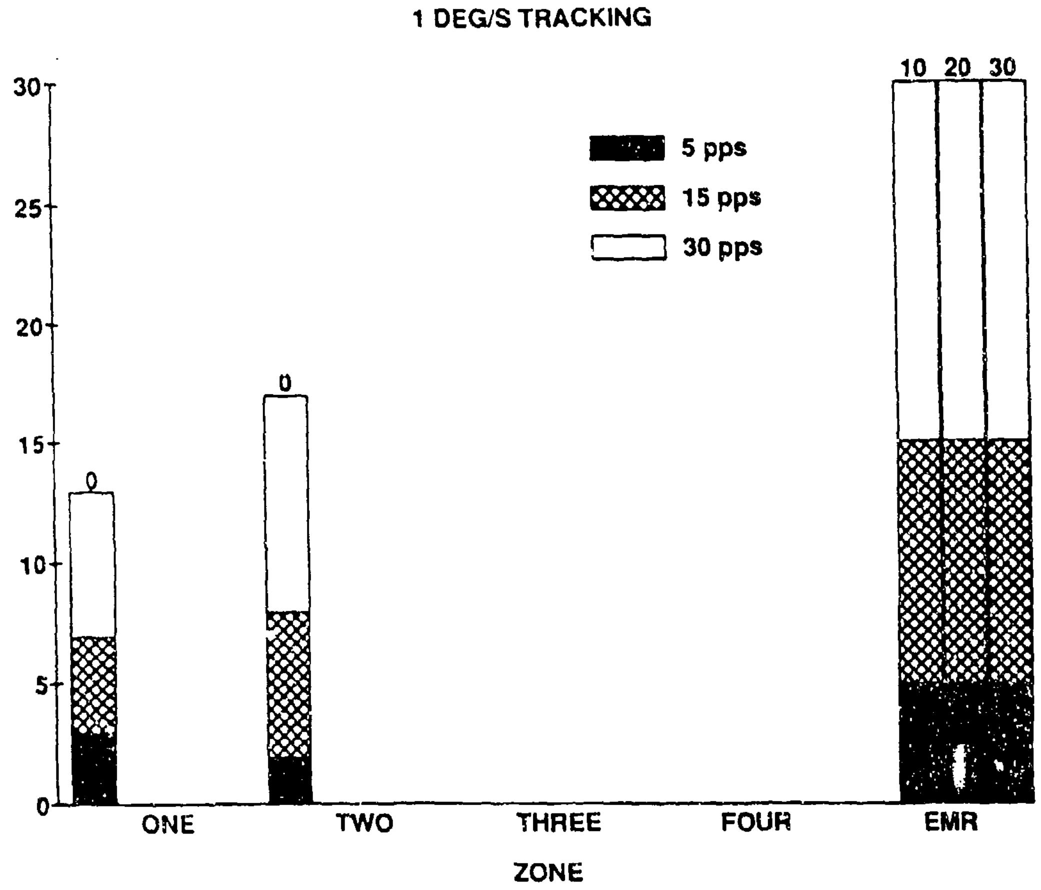

Figure 4. The number of lesions falling within various retinal zones during smooth pursuit tracking at 1 deg/s. Repetition rates and initial eccentricity of the laser are the same as in Figure 2.

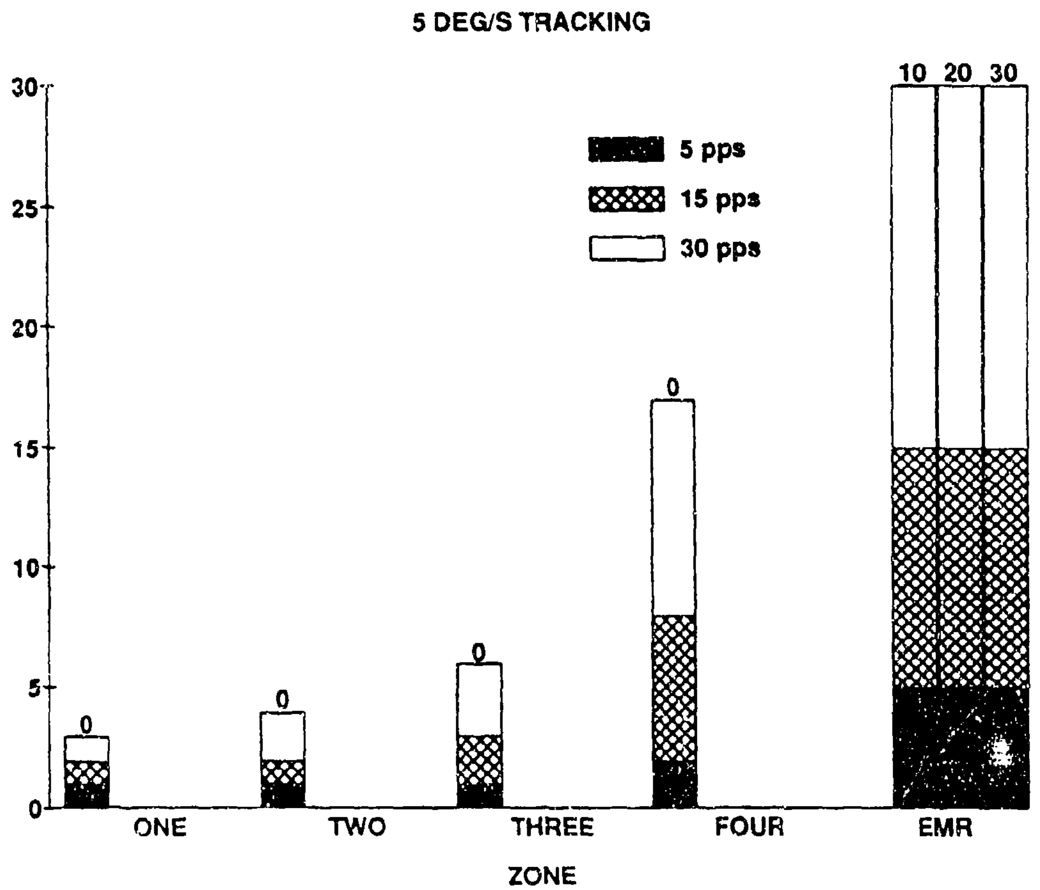

Figure 5. The number of lesions falling within various retinal zones during smooth pursuit tracking at 5 deg/s. Repetition rates and initial eccentricity of the laser are the same as in Figure 2.

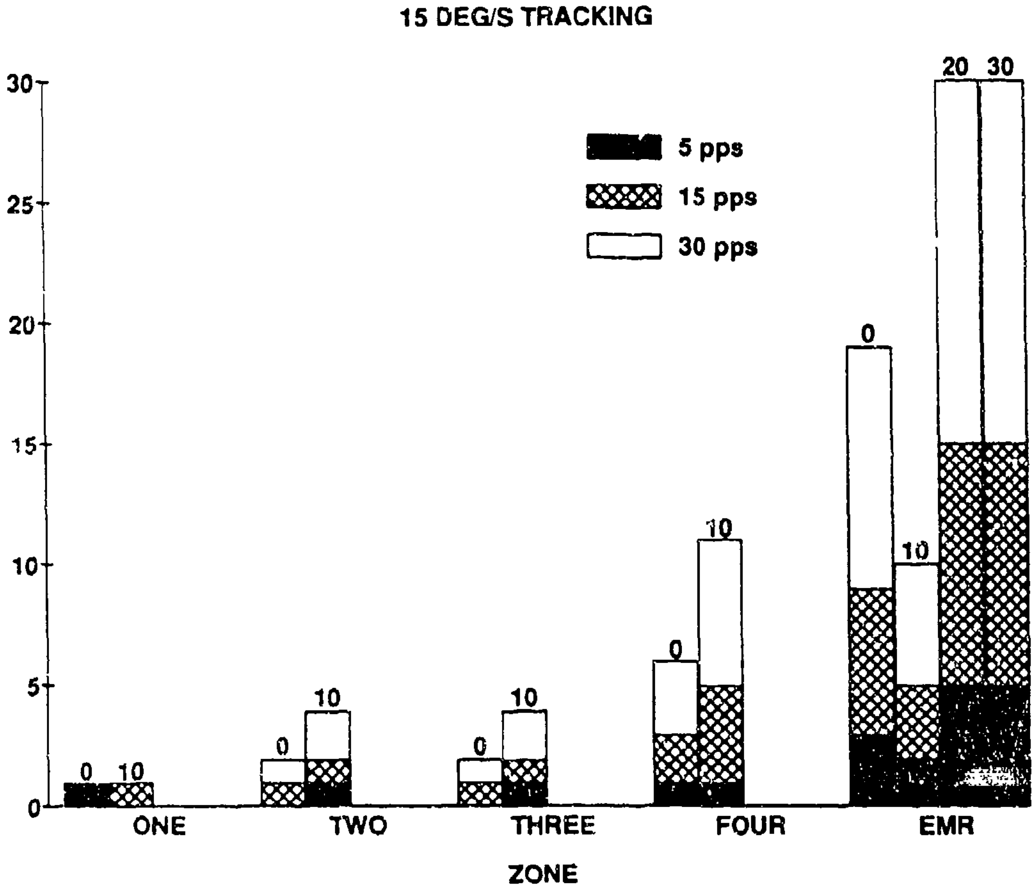

Figure 6. The number of lesions falling within various retinal zones during smooth pursuit tracking at 15 deg/s. Repetition rates and initial eccentricity of the laser are the same as in Figure 2.

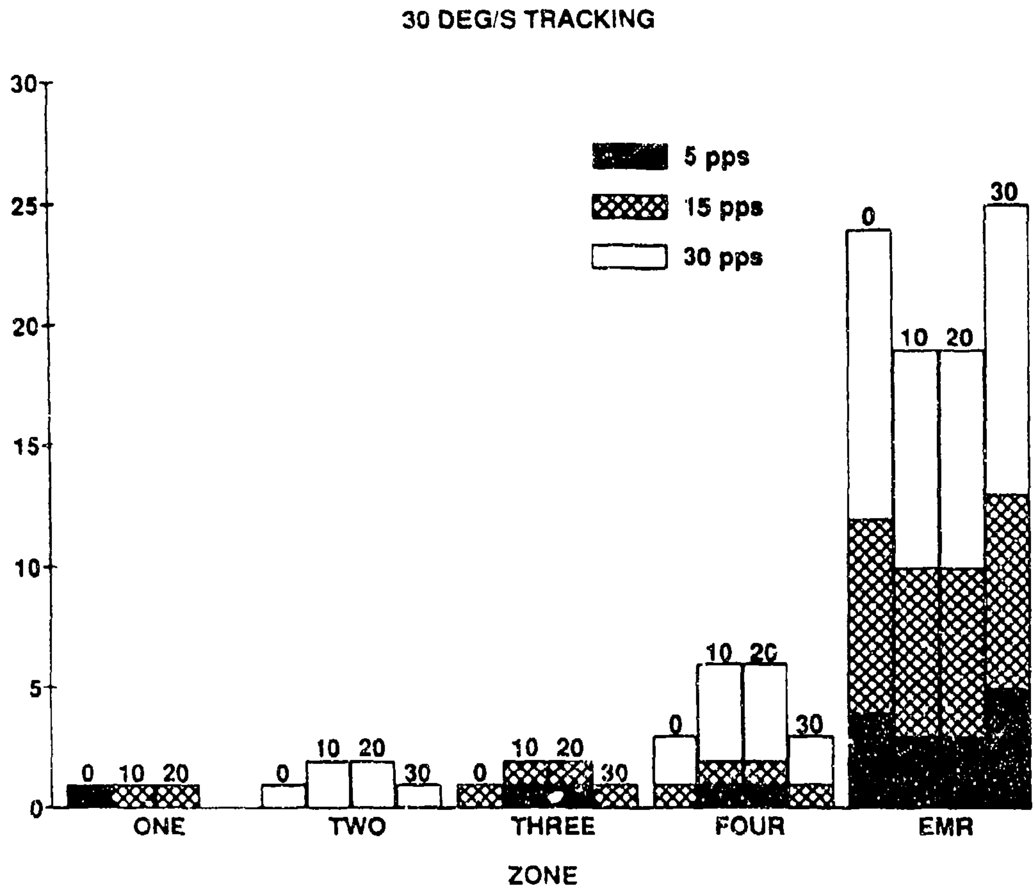

Figure 7. The number of lesions falling within various retinal zones during smooth pursuit tracking at 30 deg/s. Repetition rates and initial eccentricity of the laser are the same as in Figure 2.

closure, it would allow the pilot to maintain visual contact with his surroundings. Continued visual contact with a target during a laser exposure might be maintained if there was a large angular distance between the laser and target, or if an eye/head movement caused the eyes to be shaded from the laser. However, useful vision after foveal exposure to a high-power laser is doubtful. Data recently collected on the glare effects of a laser indicated that certain targets were completely obscured from view even at eye-safe exposure levels (17).

Other responses tended to increase the risk of eye injury. An eye movement towards the laser source increased the probability of serious visual loss by irradiating the area of highest visual acuity--the fovea. The severity of visual loss depends on the size of the retinal burns. If the number, location, and size of the lesions were such that the entire central foveal region is eclipsed, then the pilot would have to resort to eccentric fixation. Eccentric fixation decreases visual acuity (18), stability of gaze (19), and reading speed (20). This visual loss is likely to seriously affect pilot performance.

Under ideal conditions, fixation can be maintained with a great deal of stability. When the head is rigidly fixed, the target's image deviates no more than 3-6 min-arc from the foveal center, well within the region of 20/20 visual acuity (11,21,22). During flight, movement of the head and movement of the aircraft relative to the point of fixation may cause increased retinal image motion of the laser beam. Some of this retinal image motion is cancelled by the vestibular-ocular reflex, but not all (12). Thus, depending on the amount of uncompensated head and airplane motion the distribution of retinal lesions will have a radius of at least 33.8 min-arc. When the laser is viewed on-axis, the visual acuity affected is in the range of 20/20 to 20/30. Lesions would be scattered over a wider area if the pilot encounters turbulence during the exposure.

FUTURE WORK

At the present stage of development, the model predicts the distribution of lesions on the retina. However, to assess the degree of visual loss, another factor must be incorporated into the model--namely, lesion size. Factoring lesion size into the model will permit the estimation of the magnitude of the visual field loss and the associated loss in visual acuity. The size of a laser-induced lesion depends on a number of exposure parameters including wavelength, pulsewidth, pulse energy, angle of incidence, beam divergence, as well as absorption coefficients of various retinal areas. The next phase of this model will attempt to complete the picture of the threat to vision resulting from the interplay between the pilot and laser by incorporating quantitative predictions from a thermal model of laser-induced retinal lesions (1).

Although lesion size is an important factor in determining the resultant visual loss, other factors must be incorporated into the model as well. Behavioral measures must be made to determine the effect of a sudden,

unexpected, bright flash on eye movement control. Does the flash always elicit a reflexive oculomotor or blink response? What is the disruptive effect of the flash on an ongoing eye movement and can a pilot be trained to control these putative involuntary responses? Answers to these questions through empirical research would improve the applicability of the model to actual flight situations.

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